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Cork rings suggest how to manage *Quercus suber* to mitigate the effects of climate changes

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ABSTRACT

Climate scenarios in the Mediterranean region predicts raising temperatures and more frequent and extreme drought conditions. Cork oak is a Mediterranean species with a large distribution in Portugal from which cork is extracted in a sustainable way and mainly used as the raw material for cork stoppers and insulating materials. To study the response of cork oak to drought and the effect of phellogen age on that response we examined cork growth from a 30-year chronology of trees from 12 sites in the main Portuguese cork oak production area. For the first time in cork, a components resilience study was performed. The research confirmed that drought reduces cork growth and provided extra knowledge on the responses of cork oak to drought: more severe droughts correspond to higher decrease of cork growth and more trees affected but to greater recovery performance. Moreover, cork oak is very tolerant and resilient to extreme droughts. Nevertheless, there are other factors that affect cork growth during and after drought, namely site, tree and the age of the phellogen. In fact, in the first 2 years and in the last 2 years of the production cycle the effects of drought on growth are more pronounced than in the middle of the cycle. The age of the phellogen is significant in the recovery, resistance and resilience but not in the relative resilience. The most noticeable differences occurred in the recovery for phellogen under 3 years (17% lower than that for phellogen with 3 to 6 years of age). Moreover, under drought conditions, there is a strong evidence that forest managers should enlarge debarking rotations, namely if drought occurs in the first 2 years of the production cycle and/or establish new cork oak stands in more humid areas, namely, in higher latitudes than the actual species distribution area.

1. Introduction

Climate change is one of the worldwide main and challenging issues of the XXIst century requiring either a mitigation or an adaptation perspective (Stott et al., 2016). Changes in climate and, in particular, weather extremes will condition forest structure and tree species composition (Kätzel and Höppner, 2011) and consequently forest management strategies.

Although tree species can adjust to new environmental conditions, there is not much knowledge about the processes involved (Lindner et al., 2010). Nevertheless, forest managers need to adjust to this new reality and meet stakeholders needs, from a more demanding public to a more competitive and exigent forest industry.

All climatic scenarios for the Mediterranean region foresee raising temperatures, water deficits and more intense, frequent and long extreme events, in particular, severe droughts, heat waves, heavy precipitation and fewer cold days (IPCC, 2014; Lindner et al., 2010). It is predictable that this region will have a decrease in productivity and changes in species distribution as a consequence of summer water deficits (Kelly et al., 2002; Santos and Miranda, 2006; Gea-Izquierdo et al., 2013). Albeit we are only at an initial step in the forecasted tendencies of global warming, ecological responses to recent climate change are by now clearly noticeable (Walther et al., 2002) and a deeper understanding on tree response strategies should be a scientific priority (Anderegg et al., 2015; Allen et al., 2010).

One of the Mediterranean forest systems that may severely suffer from climate changes is the cork oak (*Quercus suber*) based agro-forestry system (Santos and Miranda, 2006). Cork oak forests are distributed in the Mediterranean basin, in an area of approximately 2.2 million hectares directed to an annual production of up to 200 thousand tons of cork that supply an important industry (APCOR, 2016). Portugal is the leader producer of raw cork and processed cork products namely cork stoppers for the wine industry, the most important product in all the cork segment, with the greatest added value (Pereira, 2007). The production of cork is based on a sustainable periodical stripping (usually with 9 year interval) of the cork (outer bark of the cork oak) from the

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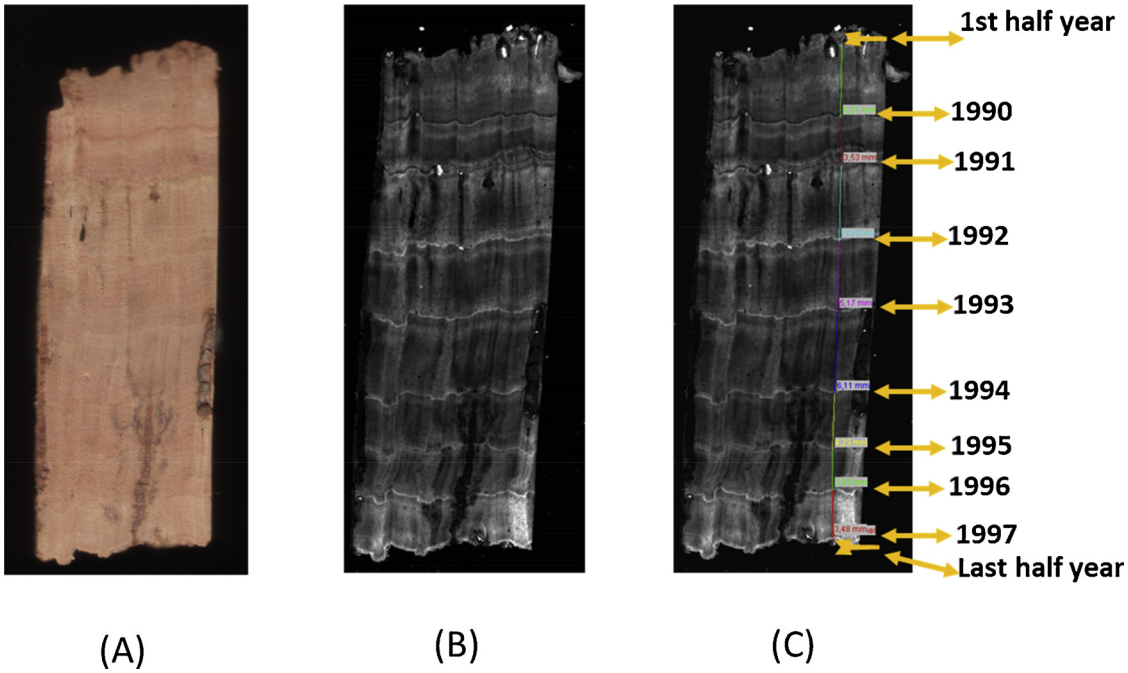

Fig. 1. A - Transverse view of a radial strip cut from a cork sample B – Fluorescence image of the cork radial strip C - Sample measured and dated, showing the two incomplete growth rings.

stem, allowing to have a plank with a thickness required for the manufacture of cork stoppers (> 24 mm).

Ecologically *Q. suber* grows well with mean annual precipitations from 600 mm to 800 mm, with 500 mm considered to be the minimum for a balanced tree development (Natividade, 1950; Pereira, 2007). However, it is susceptible to the amount and moment of precipitation, and late spring precipitation has more influence on cork oak growth than the entire annual precipitation, while it recovers quickly after a year of extreme dryness (Besson et al., 2014).

In respect to cork growth, rainfall, summer drought and temperature are determining factors and, in particular, water availability is the most constraining growth factor (Cherubini et al., 2003; Caritat et al., 2000; Costa et al., 2016; Oliveira et al., 2016) with a great effect of the precipitation from May to September on the activity of the phellogen (Pizzurro et al., 2010). Cork growth is conditioned by water availability in short time scales (from 2 to 11 months), with spring precipitation having a major effect. Moreover, cork growth rapidly recuperates when drought circumstances end (Oliveira et al., 2016).

As well as wood, cork has two different annual growth periods (spring and autumn) and annual growth rings are detectable due to the presence of a noticeable layer of darker latecork cells at the end of the growth period (Pereira et al., 1988). The rate and duration of the meristematic activity of the phellogen largely determines the width of a cork ring (Pereira, 2007).

In spite of all the research conducted so far about the relation between cork growth and climate (e.g. Caritat et al., 1996, 2000; Costa et al., 2016; Oliveira et al., 2016), there is little knowledge about the effect on cork growth of drought occurring in different moments of the 9-year cork growth cycle (e.g. beginning, middle and end), corresponding to different phellogen ages. Only a preliminary study of Leite et al. (2018) addressed this issue. Therefore, the focus of the present research is the investigation of the influence of phellogen age on the cork-growth responses to drought. This goal is addressed through a pointer year analysis followed by a resilience components study using a mixed model approach.

This publication is, as far as we know, the first analysis of resilience components on cork growth and, furthermore, the first dendroclimatic study on cork using a mixed model methodological approach. The results obtained are converted in forest management advices to mitigate the effects of the forthcoming more frequent droughts in the Mediterranean basin. This is of great importance because one of the present challenges is to transpose the ecophysiology and forest ecology scientific research into forest management prescriptions suitable for forest owners and managers (Bräuning et al., 2017).

2. Material and methods

2.1. Study area

The cork samples used in this research were collected in 12 Portuguese central-west *montado* estates placed in one of the largest continuous forest areas of cork oak and located in the Coruche municipality, Portugal. *Montado* is a multifunctional system characterized by a forest with low density trees combined with agriculture and/or pastoral activities. The sampling sites are set in the Tagus river basin, in one of the main production areas for the cork oak, characterized by a Mediterranean climate influenced by the Atlantic Ocean, as previously described in detail in Oliveira et al. (2016).

2.2. Data acquisition

A total set of 2081 cork samples, of which 1584 from Oliveira et al. (2016), was collected at breast height (1.30 m) during the stripping season in adult productive cork oak trees. The trees were randomly selected in the sites as a proportional part of the total trees under stripping. All the cork samples included 8 complete years of growth with the preceding debarking taking place 9 years before (the stripping is performed when phellogen is active leading to an incomplete cork ring). The stripping years occurred between 1994 and 2016, allowing the study of cork growth in the time span between 1986 and 2015, corresponding to a 30-year chronology, which includes several drought events occurring in different moments along the growth cycle of cork, i.e. corresponding to different ages of the phellogen.

The collected samples (± 15 × 15 cm^2) were boiled in water for 1 h at atmospheric pressure and left to air-dry until equilibrium, in a procedure similar to the one performed by the cork industry in raw

corkboards. For a more precise observation of the growth rings, the transversal sections were polished with fine sandpaper and two radial strips per sample with approximately 1 cm thickness were cut (Fig. 1A), fixed on a microscope slide and digitalized in a laser-based fluorescence imager (Fluoro Image Analyzer FLA -5100, Fujifilm, Life Science USA, Stamford, CT 06092) according to the methodology developed by Surový et al. (2009) – (Fig. 1B). Cork ring thickness was measured (Fig. 1C) with AnalySIS® image processing software (Analysis Soft Imaging System GmbH, Münster, Germany, version 3.1) and, whenever possible, along two transects in the radial direction with an accuracy of 0.01 mm. For each tree the average of the two measurements was determined.

The initial and final half rings corresponding to the years of the strippings were not considered for analysis as they are not complete growth years (see Fig. 1C). As recognized earlier by several authors (Caritat et al., 1996; Surový et al., 2009; Oliveira et al., 2016), the delimitation of annual rings was not unequivocal in all the samples, and only in 67% of the samples (1403 samples) cork rings were measured and dated. Each cork ring chronology was plotted and visually checked with TSAP-Win™ software (Rinntech, Heidelberg, Germany).

2.3. Exploratory data analysis

A brief characterization of the raw data was performed with a boxplot for the cork growth in each site, allowing to compare the sites and evaluate the respective variability. As the research focus is not the analysis of these specific sites but, instead, the potential climatic signal they reflect, the performed characterization was only for a descriptive analysis purpose.

Ring width curves were plotted for visual inspection and the sign test Gleichläufigkeit (glk) calculated using the dendrochronology program library (dplr) of the R software (Bunn, 2008; R Core Team, 2017). Gleichläufigkeit (glk) is a measure of pairwise comparison of chronologies, testing if two chronologies are simultaneously increasing/decreasing in growth at the same time (Speer, 2010); it is therefore, a measure for the likeness of tree ring curves from different trees. Furthermore, glk is a statistic that assesses the homogeneity of the samples/sites (Schweingruber et al., 1990). If in the common intervals trees respond in the same way glk is one, if they disagree glk is zero.

As usually done in dendroclimatic studies (Fritts, 1976), each cork-growth curve was plotted and standardized in order to remove systematic changes of growth associated with tree age and maximize the inter-annual fluctuations caused by the weather. In a similar approach as performed previously (Caritat et al., 2000; Costa et al., 2001; Oliveira et al., 2016), a negative exponential curve was used in the standardization process (detrend) through the early mentioned dplr library. This selection is also in accordance to Cook (1987), as the *montado* system is characterized by trees growing in open-environments with negligible competition for light. Indexation equalizes all ring width curves to an unitarian mean value, so that a tree with a large average growth will not dominate over other trees with small growth when they are put together in a mean chronology (Douglass, 1919).

This procedure fits the following model:

$$G_t = ae^{-bt} + k$$

where G_t is the growth trend and is estimated as a function of time t, being a, b and k, the coefficients. If that nonlinear model could not be fitted, then a standard linear model was adjusted $G_t = b_0 + b_1 t$ where b_0 is the intercept and b_1 the slope (Bunn, 2008).

After this procedure, for each tree, RWI - ring width indices (or cork growth indices) were calculated dividing the real cork growth (R_t) by the expected growth at time t (G_t). The division of R_t by G_t not only removes the trend in growth but also scales the variance so that it is approximately the same all over the entire period of the time series (Fritts, 1976). Furthermore, this approach also retains as much potential low-frequency climate information as possible (Fritts, 1976; Cook et al., 1990; Cook and Kairiukstis, 1990; Briffa et al., 1992).

After detrending, the signal-to-noise ratio (SNR) was calculated also with the dplR package to assess the strength of the observed mutual signal between trees (Cook et al., 1990). Furthermore, a final chronology was created with the average of the indices of all the trees and plotted (sample depth is also showed). This final index chronology contains the environmental signal common to all trees, i.e. the population signal (Fritts, 1976).

2.4. Climate data

The droughts that occurred in the 30-year period of our chronology, were characterized by the drought index *Standard Precipitation Evapotranspiration Index* (SPEI) developed by Vicente-Serrano et al. (2010) because it is one of the most generalized approaches for drought analysis, and droughts in the Iberian Peninsula are better detected with SPEI than with the *Standard Precipitation Index* (SPI) (Páscoa et al., 2017). In fact, SPEI is based on a monthly climatic water balance (precipitation minus potential evapotranspiration) and not only on precipitation data as the SPI, therefore representing a simple climatic water balance. Furthermore, as it includes temperature data, it accounts for the warming-related drought impacts on diverse ecological, hydrological and agricultural systems (Vicente-Serrano et al., 2010). Also, SPEI can be used to analyze drought at different time scales (Beguería et al., 2013; http://spei.csic.es/home.html). Furthermore, it accounts for the accumulation of deficits/overplus at diverse timescales (Drew et al., 2013).

Cork has two different annual growth periods in spring and in autumn, and is affected mainly by drought conditions from two to eleven months (Oliveira et al., 2016). The highest Pearson correlations between SPEI and cork growth (index) were found, by these authors, for time scales comprising previous winter and spring of the growth year. So, to reproduce the previous winter growing conditions we used the accumulated SPEI of April with the previous seven months (SPEI Oct-Apr) and to reflect the spring growing conditions we used the accumulated SPEI of August with the previous five months (SPEI Apr-Aug). We also used the SPEI of the hydrologic year (from October of the previous year until September of the growth year) to reflect the drought conditions of the entire year (SPEI Oct-Sep). The three accumulated SPEI data were directly retrieved from the Global SPEI database (http://sac.csic.es/spei/database.html), with a 0.5° spatial resolution for the Coruche municipality. This index is based on the FAO-56 Penman-Monteith estimation of potential evapotranspiration that is one of the most recommended for long-term climatological analysis (http://spei.csic.es/home.html). A plot with the SPEI and RWI for the 30-year period was produced to better demonstrate the relation between growth and the diverse SPEI.

In order to climatically categorize the years of our chronology, we used the classification proposed by Agnew (2000) and followed by Páscoa et al. (2017) that orders drought indices according to four classes: no drought if SPEI > -0.84; moderate if -0.84 > SPEI > -1.28; severe, if -1.28 > SPEI > -1.65 and extreme, if -1.65 > SPEI.

2.5. Pointer years

As the main interest of our research is the study of the effect of drought on cork growth and the influence of the phellogen age on the cork oak response to those climatic events, a pointer years analysis was performed. In fact, pronounced pointer years are formed in years of climatic extremes (Matisons et al., 2013; Schweingruber et al., 1990). Pointer years are years with remarkable growth responses at the stand level (Schweingruber et al., 1990). To identify a pointer year, we used the package *pointRes* of the R software (van der Maaten-Theunissen et al., 2015; R Core Team, 2017) with a relative growth change approach. We considered that a pointer year occurred when at least 55% of the trees had 30% (or more) increase/decrease in cork growth when

compared with the average growth of the preceding 2 years. Only the previous 2 years were considered because cork growth is influenced mainly by the precipitation in the previous winter and February mean minimum temperature, and not by earlier weather conditions (Oliveira et al., 2016).

For the negative pointer years, the components of resilience were also calculated (Lloret et al., 2011). In fact, these authors preconize that these components of resilience analysis can be used to better understand the mechanisms underlying resilience patterns as the recovery after drought is an indicator of individual-level resilience. Therefore, this methodology considers the following indicators (components): 1) resistance, the opposite of the decrease in ecological performance during the disturbance, and estimated by the ratio between growth during and before the disturbance; 2) recovery, that is the recuperating capacity in relation to produced damage, and estimated by the ratio between the growth after and during the disturbance; 3) resilience, defined as the ability to return to the previous ecological performance, and assessed by the ratio between the growth after and before the disturbance; and 4) relative resilience, the resilience weighted by the growth decrease experienced during the disturbance – this index is based on the concept that the impact (in this case the reduction in cork growth) during the disturbance determines the ability to reach the pre-disturbance growth. However, the interpretation of this index, at the individual level, is not unambiguous since high values can mean either a higher recovering capacity (through, for example, mobilization of stored reserves) or the effect of the decrease in the competition (due to increased neighbor mortality) (Lloret et al., 2011).

2.6. Statistical analysis

To evaluate the effect of the age of the phellogen in the ecological performance of the trees when exposed to drought (disturbance), a mixed model approach was used (Pinheiro and Bates, 2000). Although we were not interested in analyzing the covariance structure induced by the grouping of the data, the account of that variability in the model allowed to better detect the effect of our variables of interest (phellogen age and drought) than if a fixed effects model was used (e.g. ANOVA, ANCOVA or other non-parametric models). Indeed, mixed models have several advantages when compared with fixed effects models (Brown and Prescott, 2014). As highlighted by (Paulo et al., 2017) this approach has been used in several analysis of cork oak relevant tree dendrometric variables (e.g. height-diameter relation; weight of debarked cork; crown diameter and, by these authors, cork caliper). In our approach, we considered the age of the phellogen, SPEI Oct-Apr, SPEI Apr-Aug and SPEI Oct-Sep as fixed effects and site and tree nested on the site as random effects. The sites were considered random effects because they are a random sample of all the sites in the *Coruche* region, and also because we are not interested in studying the sites by themselves. The age of the phellogen was grouped in 3 classes – young (1–2 years); mean (3–6) and old (7–8).

The R package *nlme* was used for this analysis (Pinheiro et al., 2018; R Core Team, 2017), specifying the fitting method of maximum likelihood, as it is the only method that allows the estimation of the fixed effects estimators. The best model was selected with the R package *MuMIn* (Bartón, 2018; R Core Team, 2017).

3. Results

3.1. Cork growth and pointer years

The average annual cork-ring width distribution is presented in Fig. 2. The minimum value occurred in site 2 (0.78 mm) and the maximum value in site 6 (8.22 mm), corresponding to an amplitude of 7.44 mm. If the possible outliers are not considered, the most heterogeneous sites are sites 1 and 2, and site 6 is the one with the lowest amplitude. The mean values are in the range from 2.60 mm (site 6) to

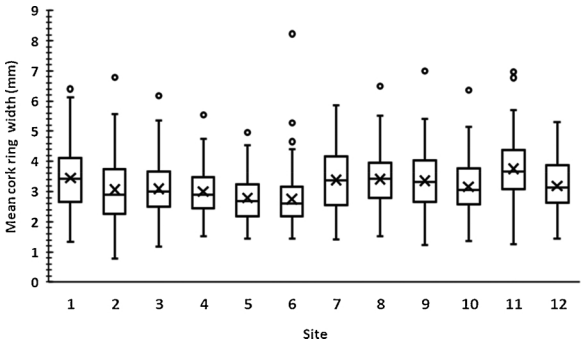

Fig. 2. Boxplot of the average annual cork ring width (mm) in each site.

3.67 mm (site 11), revealing a considerable homogeneity between sites. The mean value of the entire sample is 3.30 ± 1.44 mm.

In respect to the dendrochronological statistics, the sign test - Gleichläufigkeit (glk) presented a value of 0.656 representing a good homogeneity of the samples/sites. The SNR was considerably high – 144 times more signal than noise, the total number of trees was 1403 and the mean number of trees used to calculate SNR was 371, which reveals the robustness of the sample.

Fig. 3 shows the final mean chronology for the entire period and the respective sample depth. The mean sample depth is 370 and the minimum sample depth occurs in the years from 2012 to 2015 with almost 100 samples, also giving confidence to the results. A total of five pointer years were identified: positive (2007) and negative (1995, 1999, 2005 and 2012) pointer years are highlighted. It should be also pointed out that the cork growth index of the year immediately after a negative pointer year is always greater than 1, thereby revealing a great growth recovery i.e. growth in these years is above the mean value.

For the negative pointer years, Table 1 presents the percentage of trees that have a 30% deviation under the mean value of the growth of the previous 2 years and the mean deviation from the mean growth value of the 2 previous years. It should be noticed that the mean deviation from the mean growth in 2005 reaches almost -46% indicating a great decrease on growth due to the extreme drought conditions experienced in this year. Additionally, in all the negative pointer years more than 55% of the trees have a growth 30% under the mean value and in 2005 this value is greater than 80% revealing that the great majority of the trees were very affected by drought in this year.

Fig. 4 shows the relation between the cork-growth index mean chronology and the standard precipitation evapotranspiration index (SPEI) representative of the drought conditions in the winter before the growing season (SPEI Oct-Apr), in the spring of the growing season (SPEI Apr-Aug) and in the hydrologic year (SPEI Oct-Sep). In most of the years, there is a clear cause-effect relationship between the three SPEIs (e.g. 1986, 1987, 1988, 1995, 1996, 1999, 2002, 2005, 2007, 2009, 2010, 2011, 2014 and 2015), as to negative/positive SPEIs

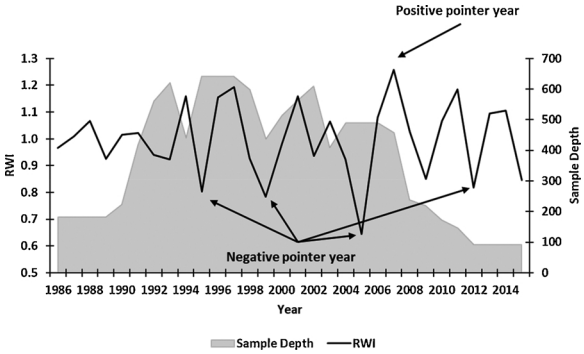

Fig. 3. Cork-growth index (RWI) chronology (in black) and sample depth of each year (grey area). Pointer years are highlighted by arrows.

Table 1
Characterization of the identified pointer years regarding the number and proportion of trees with growth decreases above 30% and mean growth deviation.

Year	Number of trees in the series	Proportion of trees with growth 30% under the mean growth of the 2 previous years (%)	Mean growth deviation from the mean growth of the 2 previous years (%)
1995	440	55.23	−30.51
1999	405	66.17	−35.26
2005	409	81.66	−45.64
2012	91	60.44	−33.36

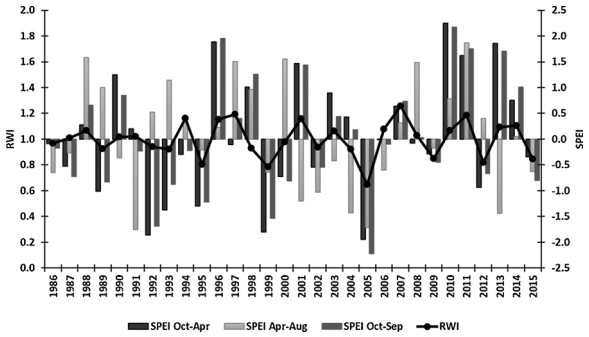

Fig. 4. Relation between cork-growth index (RWI) chronology (line) and SPEI for different timescales reflecting spring, winter and hydrologic year wet conditions (bars).

correspond a decline/increase in cork growth indices. Nevertheless, in the years when there is not a synchrony between all the SPEIs and cork growth indices, this relation occurs in at least one of the SPEIs (1989–1994, 1997, 2000, 2001, 2003, 2004, 2008, 2012, 2013). In fact, only in 1998 did a decline on cork growth index correspond to positive SPEIs while in 2006 the inverse situation occurred. It should be noticed that large negative values of SPEIs in 1992 and 1993 did not correspond to great decreases on cork growth index as already pointed out by (Oliveira et al., 2016). Further, except in 2012, all the other pointer years experienced a clear situation of drought corresponding to at least two of the SPEIs. Also, some years (e.g. 1991 and 2013) had extreme or severe drought in spring (SPEI Apr-Aug) while the cork growth index showed an above the average growth; on the contrary, in 2004, wet conditions were prevailing, but the mean cork growth index was under the mean value. Furthermore, 1992 was not considered a pointer year even if the winter prior to the growing season (SPEI Oct-Apr) and the hydrological year (SPEI Oct-Sep) were considered to have extreme drought, according to the classification proposed by Agnew (2000), and the mean cork growth was below 1.

It should also be highlighted that several authors (e.g. García-Herrera et al., 2007 and Páscoa et al., 2017) considered that 2005 had the most severe drought in the Iberian Peninsula which is in accordance to the classification of extreme drought.

Overall the analysis of Fig. 4 suggests that drought reduces cork growth and that more severe drought conditions correspond to a greater decrease in growth. However, there should be other factors affecting cork growth, rather than climate conditions since this relation is not universal (e.g. 2012 and 2004).

3.2. Resilience components

The results presented in Table 2 show that 2005, the year with the most severe drought conditions (lowest SPEI for all the time spans), is the year with the lowest mean resistance (0.54), which means, that it is the year with the major cork growth loss due to drought but also the year with the greatest mean recovery (1.62), i.e. the year with the highest recovering capacity. However, this behavior is not transversal to all the years: for example, 1999 is a year of extreme drought in the winter and severe all over the year but has the lowest recovery value (1.16), while 1995 with less severe drought conditions than 1999 in all the timespans has higher mean recovery (1.48 *vs* 1.16).

Moreover, the pointer year of 2012 with the highest SPEI for all the timespans does not stand out in any one of the calculated parameters; in fact, it has the 2nd lowest mean recovery (1.32) and relative resilience (0.16) and the 2nd highest average resistance (0.67) and resilience (0.82).

Furthermore, recovery is the component of resilience with the greatest heterogeneity (standard deviation values between 0.40 and 0.70) for all the pointer years and to the greater mean values (2005 and 1995) correspond greater variability.

It should also be pointed out that mean resilience is always at least 0.79 and in 2005 (year with most severe drought conditions) corresponds to the 2nd highest value (0.82).

The correlation between the components of resilience and SPEIs is shown in Table 3. Resistance (growth during *vs.* before drought) is highly and positively (from 0.72 to 0.88) correlated with less severe drought conditions (higher SPEI values); also, resilience (growth after vs. before drought) is positively (from 0.23 to 0.35) correlated with less severe drought conditions but less than resistance. It is also evident that recovery (growth after vs. during drought) and relative resilience (resilience weighted by reduction during drought) are positively correlated with more severe drought conditions (lower SPEI values).

3.3. Statistical analysis

The effect of the age of the phellogen in the ecological performance of the trees regarding cork growth when exposed to drought (disturbance) was evaluated by modelling the resilience components. The best linear mixed model for recovery and resilience was the full model, which means the model that included all the considered fixed effects (SPEI Apr-Aug, SPEI Oct-Apr, SPEI Oct-Sep and phellogen age), as well as the effects of site and tree, nested on site, that were considered random. The effect of the phellogen age was statistically significant in the recovery (*p-value* = 0.002) and in the resilience (*p-value* = 0.004).

The recovery of the cork growth when the age of the phellogen is less than 3 years was approximately 17% lower than when the phellogen is between 3–6 years old and when the age is above 6 years the recovery was 8% lower. The resilience when the phellogen age is above 6 years was 9% lower than when the phellogen age is between 3–6 years.

In what concerns the resistance, the best model did not include the SPEI Oct-Apr but included all the random effects. The effect of the phellogen age was statistically significant for this component (*p-value* = 4.93×10^{-14}). When the phellogen age was greater than 6 years the decrease was 14% compared to the phellogen with 3–6 years.

The best model for the relative resilience was the model that did not include the age of the phellogen but included all the SPEI's and all the random effects (site and tree, nested on site).

4. Discussion

The studies on cork growth and its relation with climate started about 20 years ago (Caritat et al., 1996) and continued since then (Caritat et al., 2000; Costa et al., 2001, 2016; Oliveira et al., 2016 and Leite et al., 2018). Also, the response of trees, communities and

Table 2
Drought conditions in winter (SPEI Oct-Apr), spring (SPEI Apr-Aug) and hydrologic year (SPEI Oct-Sep), mean and standard deviations of each one of the resilience components calculated for the negative pointer years (1995, 1999, 2005 and 2012).

Year	Drought conditions			Mean recovery	Mean resistance	Mean resilience	Mean relative resilience
	SPEI Oct-Apr	SPEI Apr-Aug	SPEI Oct-Sep				
1995	**severe** −1.30	**no drought** −0.21	**moderate** −1.22	1.48 ± 0.70	0.70 ± 0.22	1.01 ± 0.28	0.31 ± 0.33
1999	**extreme** −1.81	**no drought** −0.64	**severe** −1.54	1.16 ± 0.42	0.65 ± 0.28	0.79 ± 0.28	0.06 ± 0.26
2005	**extreme** −1.94	**extreme** −1.71	**extreme** −2.22	1.62 ± 0.61	0.54 ± 0.20	0.82 ± 0.23	0.27 ± 0.23
2012	**moderate** −0.94	**no drought** 0.40	**no drought** −0.66	1.32 ± 0.40	0.67 ± 0.23	0.82 ± 0.24	0.16 ± 0.19

ecosystems to short-term disturbances has been widely explored as described by Lloret et al. (2011). Nevertheless, this present research on cork growth is, as far as we know, the first one on disturbance analysis through a component resilience approach.

The mean values reported in this study for cork ring width (3.30 mm) are in accordance to the ones reported by several authors for the cork oak and also encompass the variability between trees and sites that is consistently reported. In fact, the values found for cork ring width by different authors are in the range from 2.8 to 3.6 mm (3.30 mm and 3.56 mm by Caritat et al., 2000; 3.8 mm by Costa et al., 2002; 3.5 mm by Pereira, 2007; 3.3 mm by Oliveira et al., 2016; 3.6 mm, 3.1 mm and 2.8 mm by Costa et al., 2016). In a large cork sampling covering all the production regions in Portugal, a mean value of cork ring width of 3.6 mm was reported ranging from site means of 1.6 mm to 4.6 mm (Lauw et al., 2018).

The high number of samples analyzed (1403, with a minimum of 91 samples/year, Fig. 3) allowed us to better account for the variability of the entire population of interest and therefore to have better estimations. This sampling intensity combined with the high value of the SNR (144) are strong evidences of the reliability of our results.

We confirmed the outcomes of several authors about the negative effect of drought on cork growth (Caritat et al., 1996; Costa et al., 2016 and Oliveira et al., 2016), reinforcing that the spring and winter rain strongly influences phellogen activity. Furthermore, our results (Table 1) demonstrated that more severe drought conditions correspond to greater decreases in cork growth and to more trees affected by drought, although, as pointed out by Oliveira et al. (2016) and Besson et al. (2014), cork oak rapidly recovers as water availability increases, achieving previous ecological performance (see Table 2 and Fig. 4).

Our analysis demonstrated that the age of the phellogen is a relevant factor on the recovery and on the resilience of cork oak regarding cork growth and that the younger the phellogen (up to 2 years) the greater the effect of the drought on growth. These findings are not in accordance to the previous results (Leite et al., 2018), that supported the hypothesis that the age of the phellogen has no influence on the magnitude of cork growth decline in response to drought. However this assumption was supported on data from a small sampling and number of drought events (3 sites, 149 samples and 1 drought event). The present study expanded the number of sites and samples (12 and 1403) and analyzed various drought events/pointer years (4) while applying a methodology of analysis of resilience components instead of cork growth indices with a mixed model approach that better detect the effect of the variables of interest.

These findings reinforce the importance of the sampling size in evaluating biological/ecological processes namely when a large growth and response variability is present, such as it is the case of the cork oak and cork growth.

Additionally, the results (Table 2) suggest that more severe droughts correspond to lower resistance values, which means, greater the effects of the drought on the growth of the drought year. The trade-off between resistance and recovery after drought, as identified by (Galiano et al., 2011) and highlighted by (Lloret et al., 2011), that states that resistance and recovery depend on the quantity of stored reserves was confirmed here, with the lowest value of resistance corresponding to the highest recovery. A low resistance indicates reserve consumption during drought but if there is recovery after drought then there is a positive effect from the regaining of photosynthetic capacity after drought (Galiano et al., 2011).

Nevertheless, there is not a clear pattern between the severity of drought and the recovery, resistance or resilience behavior and there is a great variability on the performed recovery (Table 2 and statistical analysis). The same conclusions were achieved by (Lloret et al., 2011) who got miscellaneous results for the impact of drought on subsequent tree performance and concluded that tree responses to disturbance are extremely complex. These authors also referred that micro-site quality is a more determinant factor in response to disturbance than physiological or structural factors.

The mean resilience values were in general higher than 0.80 (Table 2) showing that post-drought cork growth is close to pre-drought (unitary resilience indicates similar growth values before and after drought) and demonstrating that cork oak has a great capacity to recuperate the previous ecological performance. Therefore, the impact of drought on cork growth of the subsequent years was moderately low, supporting the hypothesis that cork oak is very tolerant and resilient to extreme droughts. Similar results and conclusions were achieved regarding wood growth for other Mediterranean species (*Pinus nigra*, *P. sylvestris* and *Juniperus communis*) (Herrero and Zamora, 2014) although not for another oak (*Q. faginea*) (Granda et al., 2013). *P. sylvestris* needs more time than *Q. pyrenaica* to recover from drought (Gea-Izquierdo et al., 2014). Regarding this, species acclimated to more humid environments may be more susceptible to drought as reported for *Q. ilex* (Granda et al., 2013).

Table 3
Pearson correlation coefficients between the mean annual components of resilience and SPEI for different timescales reflecting spring, winter and hydrologic year wet conditions.

	Mean annual resistance	Mean annual recovery	Mean annual resilience	Mean annual relative resilience
SPEI Apr-Aug	0.88	−0.52	0.27	−0.24
SPEI Oct-Apr	0.72	−0.18	0.35	0.05
SPEI Oct-Sep	0.83	−0.49	0.23	−0.23

The results of this research also enforce that the occurrence of wet conditions in winter, spring and the whole year are determinant to cork growth, during and after drought, but there are other factors involved, namely the site, the tree and the age of the phellogen. This issue was raised by Sánchez-González et al. (2007) by stating that there is a relationship between cork growth and "unobservable site factors" rather than average climatic conditions.

Moreover, the ability to recover (expressed by the relative resilience) does not seem to be affected by the age of the phellogen. It should be stressed that the phellogen age range in the present research is only between 1–8 years, therefore not allowing to extrapolate the response for much older meristems. For instance Lloret et al. (2011) found no overall decrease in all the resilience components in old trees, supporting the hypothesis that old trees recover better from more recent events.

Also, there is still lack of information about the minimum threshold for the recovery of cork growth, which means that it is still unknown which are the drought conditions in which this species no longer is able to recover. As more frequent drought conditions are expected, further investigation is needed on the question if the response to drought conditions remains high after more repeated droughts.

Furthermore, it should also be interesting to analyze not only the effect of the age of the phellogen but also the effect of the age of the tree on the post-drought response. Other future research opportunities could also be related to the simultaneous analysis of these resilience components on the growth of the wood and of the cork, to have a deeper insight in the highly complex phenomena involved under cork oak drought responses. These issues could contribute to a better knowledge regarding cork oak vulnerability to drought and should be considered in a forest management strategy under a context of adaptation/mitigation of climate change effects in the Mediterranean region.

Transposing our dendroecological results to forest management we preconize that cork growth cycles should be enlarged in case of occurrence of drought and when the production records suggest that the reduction on growth due to drought may lead to obtain cork planks under 24 mm, and particularly if the drought occurs in the first two years of the production cycle. This management directive lies on the economic rationale of not compromising the technological possibility to produce cork stoppers (Lauw et al., 2018). The extension of the cork stripping rotation in order to mitigate the effect of climate change was also proposed by (Palma et al., 2015) and (Leite et al., 2018).

Moreover, the predicted scarcity of water in the actual distribution area of cork oak also suggests that new cork oak plantations should be shifted into more humid areas (higher latitudes) where, in the nearest future, the annual precipitation will be more adequate for the balanced cork oak development and thereby allowing the maintenance of the production of cork planks thick enough to manufacture cork stoppers with the usual 9-year cycle.

5. Conclusions

In a changing climate, Mediterranean ecosystems are expected to be under more severe, frequent and extreme drought conditions similar to the ones analyzed in this research. Our results show that dry spells have a strong impact on cork growth and the more severe the drought the greater the reduction on growth but also the greater the recovery performed. Moreover, although the effects of drought persist, the recovering capacity of cork oak is not affected even in drought conditions as severe as the ones from 2005. Therefore, we advise forest managers of the Mediterranean region to continue to produce cork as, according to our findings, it is expected that cork oak recovers from the growth reduction imprinted by drought.

Nevertheless, there are other factors that affect the performance of cork growth during and after drought, namely site, tree and the age of the phellogen, and have an important role on the responses of cork oak to drought and on its ability to recover. The effects of drought on growth are more pronounced in the first two years and in the last two years of the cork production cycle than in the middle of the cycle.

The results of this study demonstrate that cork oak is very tolerant and resilient to droughts, has a great capacity to recover from water scarcity conditions, reflecting its high adaptation to the variability of water availability in the Mediterranean region. Our research also demonstrates that cork-ring data analyses may be adequate to detect signals of cork oak response to less water availability in a nearest future.

Furthermore, there is a strong signal for forest managers to extend the cork stripping rotation in case of drought, namely if the drought conditions occur in the beginning of the production cycle (first 2 years) and if there is the risk that cork planks are under 24 mm thickness as given by the past history of the site. Moreover, our results also suggest that in a context of more frequent and severe drought episodes, new cork oak plantations should be established in more humid zones (e.g. higher latitudes) to ensure the production, in a 9-year cycle, of cork planks thick enough to produce cork stoppers.

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